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AN EMPIRICAL CORRELATION OF CRITICAL BOILING HEAT FLUX IN FORCED FLOW UPWARD THROUGH UNIFORMLY HEATED TUBES

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SUMMARY

A correlation study is made of some of the experimental maximum critical heat-flux data (burnout condition) obtained from boiling heat-transfer research using water, hydrogen, and nitrogen as the working fluids. The data studied herein were all obtained using upward flow through uniformly heated circular tubes for conditions of net vapor generation. The water data used covered a range in working pressures from 14.7 to 2000 pounds per square inch absolute, while the cryogenic-fluids data were obtained at 50 pounds per square inch absolute. An empirical correlation for predicting the maximum critical heat flux (burnout condition) is presented. Correlation is achieved through the development of an enthalpy ratio or critical vaporization parameter and a function consisting of several dimensionless groups containing variables that include fluid mass velocity, tube geometry, and fluid property terms. All fluid property terms are evaluated at the fluid saturation temperature associated with the burnout condition.

INTRODUCTION

In the development of boiling heat-transfer devices for use with space vehicles a variety of fluids having a wide range of boiling points is being considered. Furthermore, in certain reactor designs consideration is being given to permit some boiling to take place within the reactor.

The advantages of vaporizing a fluid in the nucleate-boiling heat-transfer regime are apparent when the large heat-flux values obtainable with this type of boiling are considered in terms of the accompanying low wall-to-fluid bulk temperature differences. Vaporization of fluid in the nucleate-boiling regime leads to efficient and lightweight heat exchangers or boilers. However, the possibility of transition from the nucleate- to the film-boiling regime, with its accompanying high wall-to-fluid bulk temperature differences, can result in the destructive failure of the containment material or component. The heat flux associated with the transition from nucleate-bulk to film boiling is herein called the critical heat flux. For a flowing system this critical heat flux can be defined as the flux immediately before the transition from a high heat-transfer coefficient to a lower value at an arbitrary location along the channel or tube axis. The point along the tube at which this transition in heat-transfer coefficient occurs is frequently called the burnout point because of the possibility of material failure. The distance, measured along the tube axis, from the tube inlet to the burnout point or location is herein designated the critical length.

An analytical solution of the critical-heat-flux problem in boiling has not as yet been obtained. The correlation of critical-heat-flux data in the form of empirical dimensionless parameters, however, is of great usefulness for engineering applications. As is evident from surveys of the numerous critical-heat-flux correlations in the literature, correlations for forced-flow systems, while at times successfully correlating the results from a limited single study or studies of closely related fluids, have not met with significant success when applied to fluids having widely different properties and ranges of flow conditions (ref. 1).

In the present study, conducted at the NASA Lewis Research Center, empirical parameters were developed in order to correlate the maximum critical-heat-flux values for forced flow in terms of a vaporization parameter that was found to vary as a function of fluid flow rate, tube geometry, and fluid properties (including pressure level of the fluid). The study is limited to upward flow through uniformly heated circular tubes and to conditions of net vapor generation. The developed fluid property parameters correlate fluids having such widely varying properties as hydrogen, nitrogen, and water. The data used cover a range of pressures at the burnout locations from 14.7 to 2000 pounds per square inch absolute for water and 50 pounds per square inch absolute for hydrogen and nitrogen.

DATA SELECTION PROCEDURES

Critical-heat-flux values differing by over 100 percent can easily be obtained in a particular research loop. These differences frequently can be attributed to: (1) the introduction of a compressible volume upstream of the heated test section (ref. 2), (2) insufficient pressure drop upstream of the heated test section, (3) techniques used in establishing a critical-heat-flux condition (ref. 3), or (4) gas content of the liquid (ref. 2). Other factors may also cause similar effects, but have not been sufficiently identified or verified. These effects always produce low critical-heat-flux values. Since about 1955 the preceding effects have been recognized and minimized by researchers because of a better understanding of two-phase flow problems. However, most researchers have not identified their data to permit segregation of that which can be considered maximum critical-heat-flux values from that which is influenced by the preceding phenomena.

Thus, in the analysis of critical-heat-flux data reported in the literature, it is considered reasonable and necessary to screen the data and discard that which appears to be associated with the effects noted in the previous paragraph.

The following method was applied for the selection of data used herein to obtain a correlation of the maximum critical-heat-flux envelope:

(1) The data of table III of reference 2, because they were reported more fully than most other results in the literature, were considered representative of valid maximum critical-heat-flux data for stable flow conditions. Analysis of these data showed that, in terms of a critical vaporization parameter (defined later herein), the data generally fell into a scatter band of approximately 70 to 100 percent of the maximum critical vaporization parameter obtained at a particular flow condition. This 70-percent factor was applied to all other data used herein; all data showing a greater deviation were discarded.

(2) In the event that the maximum critical vaporization parameter values for a particular study, all other conditions constant, were considerably below those reported in one or more other studies, these values were discarded if they were below 70 percent of the maximum values reported in the other studies.

(3) Only those data were used for which net vapor generation was reported.

(4) Isolated data points (less than five) that greatly exceed the mass of the maximum critical vaporization parameter data points were discarded.

Table I lists the total number of critical-heat-flux data points associated with net vapor generation in the references used herein, those selected for the present correlation based upon the preceding selection method, and the range of variables covered in the references cited. It should be noted that for the nitrogen and water data the burnout location occurred at the tube exit, while for the hydrogen it occurred within the tube upstream of the tube exit. The latter was possible since the heated wall temperatures with hydrogen did not exceed those necessary to cause tube material failure.

DEVELOPMENT OF CORRELATION PARAMETERS

Critical Vaporization Parameter

In vaporizing a fluid, two heat-transfer parameters appear to be of immediate significance: (1) the critical heat input for specific flow conditions and tube geometries so that a burnout condition can be avoided, and (2) the heat addition or total enthalpy required to vaporize all the fluid. The ratio of these two parameters is herein designated as the critical vaporization parameter X_C. (All symbols are defined in appendix A.)

For a critical-heat-flux condition, the heat addition from the tube inlet to the burnout location per pound mass flowing is Q_C/W. For circular tubes with uniform heat flux, Q_C/W can be conveniently written as:

$$\frac{Q_C}{W} = \frac{q_C \pi DL}{G \frac{\pi D^2}{4}} = \frac{4q_C}{G} \frac{L}{D} \tag{1}$$

The enthalpy increase required to vaporize all the inflowing liquid in a heated tube to saturated vapor at the burnout condition is:

$$\Delta h = h_v - h_l \tag{2}$$

Equation (2) requires that the inlet pressure and temperature be known. For the water data, however, only the pressure coincident with the burnout location at the tube exit was measured. Tube inlet and exit pressures were measured for the hydrogen and nitrogen data (ref. 3) but for the test conditions were substantially the same. Consequently, the exit pressure for these two fluids was used to determine the enthalpy condition at the burnout location, even when the latter was within the tube, as in the case for hydrogen.

In view of the limitations of the pressure information at the inlet, equation (2) was simplified by neglecting the effect of pressure on the enthalpy of the liquid at the tube inlet and written as:

$$\Delta h \cong h_v - (h_l)_{t_i} \tag{3}$$

The difference in Δh values computed by equations (2) and (3) is considered negligible; for example, for water the difference is less than 11 Btu per pound or for the data used herein less that 1 percent. Equation (3) was used throughout this report.

From equations (1) and (3) the critical vaporization parameter X_C is then written as:

$$X_C = \frac{\frac{Q_C}{W}}{\Delta h} = \frac{\frac{4q_C}{G}\frac{L}{D}}{\Delta h} \tag{4}$$

When liquid at the tube inlet is saturated (no subcooling), X_C is identical to the conventional definition of fluid quality. Furthermore, when X_C is 1.0, the fluid quality is also 1.0. Equation (4) was used throughout this report. It should be noted at this point that all data matching for correlation purposes was done by shifting the curves horizontally on the abscissa scales and that the ordinate scale is always X_C given by equation (4).

Forced-Flow Considerations

A typical plot of the variation of critical heat flux for upward flow through a circular tube with mass velocity, using water with substantially constant values of inlet temperature, tube diameter, critical L/D ratio, and exit pressure at the burnout location (14.7 lb/sq in. abs) is shown in figure 1 (data from ref. 2). The critical-heat-flux curve increases with increasing mass velocity but with a decreasing slope. When the critical heat flux is plotted in terms of the critical vaporization parameter X_C (also shown in fig. 1), the value of this parameter increases with decreasing mass velocity, asymptotically approaching a value of 1.0 (complete vaporization or 100-percent quality).

Tube Geometry Considerations

The primary tube geometry factors that were observed to affect the critical vaporization parameter for conditions of net vapor generation in the reference literature were tube diameter and the ratio of tube length (measured from tube entrance to the burnout point) to tube diameter. Other factors, such as tube surface condition, tube material, and tube orientation other than vertical, are insufficiently documented for inclusion in the present empirical analysis.

Effect of tube diameter on critical vaporization parameter. - The effect of tube diameter on X_C was established from a plot of X_C as a function of mass velocity for various tube diameters with constant values of liquid inlet temperature, exit pressure, and critical L/D ratio. Such a plot, using water data from table III of reference 2 (14.7 lb/sq in. abs at the burnout location) and considered representative of all data therein, is shown in figure 2(a) for a critical L/D ratio of 100 and six tube diameters ranging from 0.051 to 0.188 inch. It was determined that X_C varies directly with tube diameter and could be correlated as a function of the product GD for constant values of critical L/D ratio. The parameter X_C is shown as a function of the product GD in figure 2(b) for a critical L/D ratio of 100; the data are seen to be no longer a function of tube diameter. The relation of X_C to GD determined for water at low pressure is assumed to be valid for other fluids and pressures.

Effect of critical tube length-to-diameter ratio on critical vaporization parameter. - The typical variation of X_C with critical tube length-to-diameter ratio for water is shown in figure 2(c) for various mass velocities, a tube diameter of 0.076 inch, critical L/D ratios of 50 to 250, and a pressure of 14.7 pounds per square inch absolute at the burnout location (ref. 2). The critical vaporization parameter X_C varies directly with critical L/D ratio and can be correlated by $GD/(L/D)^{1.3}$ as shown in figure 2(d). The same parameter correlates the data for other tube diameters reported in reference 2 and is assumed to be valid for other fluids and pressures.

Fluid Property Considerations

Effect of pressure at burnout location on critical vaporization parameter. - An examination of the selected critical-heat-flux data for water at pressures over 500 pounds per square inch absolute (refs. 4 to 10) shows that X_C is a function of fluid pressure level. Typical of these data are those shown in figure 3 in which X_C is plotted as a function of $GD/(L/D)^{1.3}$ for fluid pressures (at the burnout location) of 500 to 600 (fig. 3(a)), 1000 (fig. 3(b)), and 2000 pounds per square inch absolute (fig. 3(c)). For comparative purposes the average curve for the data of reference 2 (14.7 lb/sq in. abs) is also shown in figure 3. It is apparent that for a given X_C value the $GD/(L/D)^{1.3}$ term is greater at fluid pressures of 500 to 600 and 1000 pounds per square inch absolute than at either 14.7 or 2000 pounds per square inch absolute; in fact, the latter two pressure levels yield nearly the same X_C values for a given $GD/(L/D)^{1.3}$ value.

Effect of fluid on critical vaporization parameter. - In figure 4 X_C is shown as a function of $GD/(L/D)^{1.3}$ for hydrogen and nitrogen, both fluids at a pressure at the burnout location of 50 pounds per square inch absolute (ref. 3), together with the average curve for the low-pressure water data of reference 2. In general, the trends of the cryogenic fluids data are similar to those for the water data. The scatter of the cryogenic data is random and of a similar magnitude as that for the water data.

Fluid property parameters used for correlation of critical vaporization parameter. - It is evident from figures 2 to 4 that the variation of X_C with $GD/(L/D)^{1.3}$ is a function of both the specific fluid and the pressure level. Their combined effects on critical-heat-flux data are herein considered to be a function solely of fluid properties.

In order to achieve a general and practical solution for X_C in terms of fluid properties, it is convenient to use nondimensional parameters. A literature survey indicates that numerous heat-transfer and flow parameters containing fluid property terms have been evolved through either theoretical or empirical studies. These parameters include, among others, Reynolds number, Weber number, Froude number, Prandtl number, and Bond-Newton number, as well as several ratios of vapor-to-liquid fluid properties. Certain of these parameters were considered herein to be significant and were selected to serve as a base for a correlation of the data shown in figures 2 to 4. Because GD was already established as a primary correlation factor, this term was converted into Reynolds number by dividing it by the saturated vapor viscosity at the burnout condition. It was also arbitrarily assumed that the saturated vapor Prandtl number at the burnout condition was a significant parameter. In the selection of the saturated vapor properties for these parameters the burnout condition was considered to be associated with a formation of sufficient vapor bubbles or a vapor film to insulate the heated wall tube from the liquid portion of the fluid. This insulation effect prevents adequate heat transfer from the heated wall to the bulk of the fluid and causes the wall temperature of the tube to increase markedly, sometimes to a critical or burnout value with respect to the containment material. An exponent of 0.4 was arbitrarily assigned to the Prandtl number since much of the convective heat-transfer data and some of the boiling studies in the literature have indicated a dependency on an exponent of this order of magnitude. Therefore, as the first step in the present correlation, it was assumed that:

$$\begin{aligned} X_C &= f\left[\frac{GD}{(L/D)^{1.3}}\,\frac{Pr_V^{0.4}}{\mu_V},\ \text{other fluid properties}\right]_s \\ &= f\left[\frac{Re_V Pr_V^{0.4}}{(L/D)^{1.3}},\ \text{other fluid properties}\right]_s \end{aligned} \tag{5}$$

With respect to the data shown in figures 2 to 4, the use of Reynolds and Prandtl numbers will merely shift the data horizontally, in some cases interchanging the location of the data curves for the various fluids with respect to each other.

Through a study of the various nondimensional relations and trial-and-error determinations a dimensionless fluid property parameter was obtained that, together with equation (5) and additional ratios of density and viscosity, provided the necessary correlation of all the experimental data. The dimensionless fluid property parameter that was obtained consists of:

$$\frac{\sqrt{g}\ \mu_v^2\ \sqrt{\rho_l - \rho_v}}{\rho_v(g_c\sigma_l)^{1.5}} = N_B \tag{6}$$

and is arbitrarily designated herein as a boiling number N_B. The ratios of density and viscosity are written respectively as:

$$\frac{\rho_l - \rho_v}{\rho_v}$$

and

$$\frac{\mu_v}{\mu_l}$$

All fluid properties in equation (6) and the previous parameters are evaluated at the saturation temperature associated with the burnout location. Examination of equation (6) shows that the boiling number N_B consists of fluid property relations similar to those expressed in Reynolds number, Weber number, and Bond-Newton number.

The complete fluid property correlation parameters evolved to the following relations:

$$\frac{X_C}{f\left[\frac{GD}{(L/D)^{1.3}}\right]} = f\left[\left(\frac{Pr_v^{0.4}}{\mu_v}\right)\left(\frac{\mu_v}{\mu_l}\right)^a\left(\frac{\rho_l - \rho_v}{\rho_v}\right)^b(N_B)^c\right]_s \tag{7}$$

A solution for the exponents in equation (7) was obtained by trial and error. The best match of all the data used herein was obtained with the following exponents:

$$a = 1.7,\ b = 0.4,\ c = 1.0 \tag{8}$$

With these exponents equation (7) is then written as:

$$\frac{X_C}{f\left[\frac{GD}{(L/D)^{1.3}}\right]} = f\left[\left(\frac{Pr_V^{0.4}}{\mu_V}\right)\left(\frac{\mu_V}{\mu_l}\right)^{1.7}\left(\frac{\rho_l - \rho_V}{\rho_V}\right)^{0.4}(N_B)^{1.0}\right]_s \tag{9}$$

A brief discussion of the significance of the individual fluid property terms as well as the effects of combining several of these terms on the correlation of data is given in appendix B.

Complete Critical-Heat-Flux Correlation

The complete correlation equation for the determination of the critical vaporization parameter is expressed from equation (5) by the following relation:

$$X_C = f\left\{\left[\frac{Re_V Pr_V^{0.4}}{(L/D)^{1.3}}\right]\left(\frac{\mu_V}{\mu_l}\right)^{1.7}\left(\frac{\rho_l - \rho_V}{\rho_V}\right)^{0.4}(N_B)\right\}_s \tag{10}$$

The low-pressure water data of reference 2 in terms of equation (10) are shown in figure 5(a). The use of the fluid property parameters for these data does not affect the actual data correlation because for these data the fluid property parameters are substantially constant; however, the mass of the data permits the establishment of an average curve (shown by the dot-dash line) and ±15-percent scatter-band limits from this average value curve. These curves then serve as a basis for comparison with water data at other pressures and also with data for other fluids. It should be noted that the ±15-percent scatter band results from the data selection method previously discussed.

A plot of the selected water data for the maximum critical-heat-flux values at pressures of 500 to 2000 pounds per square inch absolute (refs. 5 to 10) in terms of equation (10) is shown in figure 5(b). It is apparent that the X_C trend with fluid pressure noted in figure 3 has been accounted for by the fluid property parameters developed herein.

The cryogenic data from reference 3 are shown in figure 5(c) in terms of equation (10) together with curves representing the average and scatter bands of the low-pressure water data of reference 2. The cryogenic data now correlate, whereas before the application of the fluid property parameters (fig. 4) two distinct curves, one for each fluid, were obtained. Good correlation is also apparent between the cryogenic fluids and water, indicating that, for the ranges of variables and fluids involved, the critical vaporization parameter can be correlated, and the critical-heat-flux values can be determined using the relations of equation (10) and figure 5.

CONCLUDING REMARKS

From an analysis of boiling heat-transfer data obtained with water, hydrogen, and nitrogen, an empirical equation was evolved that correlates the critical heat flux (burnout condition) for net vapor generation over a wide range of operating conditions for forced-flow upward through uniformly heated, circular tubes. Correlation was achieved by the development of a relation between a critical vaporization parameter X_C and a function consisting of several dimensionless groups containing variables believed to influence boiling. The parameter X_C is defined as the ratio of the total heat input from the tube entrance to the burnout location on the heated tube per unit mass flow to the enthalpy difference between the saturated vapor at the burnout location and the liquid at the tube inlet. The complete correlation, for conditions resulting in net vapor generation, can be written as:

$$X_C = f\left[\left(\frac{Re_v Pr_v^{0.4}}{(L/D)^{1.3}}\right)\left(\frac{\mu_v}{\mu_l}\right)^{1.7}\left(\frac{\rho_l - \rho_v}{\rho_v}\right)^{0.4}\left(\frac{\sqrt{g}\,\mu_v^2\,\sqrt{\rho_l - \rho_v}}{\rho_v(g_c\sigma_l)^{1.5}}\right)^{1.0}\right]_s$$

where the fluid property symbols are those conventionally used in heat-transfer studies. All fluid properties are evaluated at the saturation temperature associated with the burnout location. The subscripts v and l refer to vapor and liquid, respectively, while s refers to the saturated state of the fluid at the burnout location.

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National Aeronautics and Space Administration
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APPENDIX A

SYMBOLS

c_p — fluid specific heat, Btu/lb_m, ^oR

D — tube diameter (I.D.), ft

f — functional notation

G — mass velocity (flow rate per unit cross-sectional area of tube), lb_m/hr, sq ft

g — acceleration (gravity), 4.17×10^8 ft/hr^2

g_c — conversion constant between lb_f and lb_m, 4.17×10^8, $\frac{lb_m}{lb_f} \times \frac{ft}{hr^2}$

Δh — total enthalpy change required for complete vaporization of incoming fluid, Btu/lb_m

h_l — enthalpy of liquid at inlet conditions, Btu/lb_m

$(h_l)_{t_i}$ — enthalpy of liquid saturated at inlet temperature, Btu/lb_m

h_v — enthalpy of vapor saturated at conditions associated with burnout location, Btu/lb_m

k — fluid thermal conductivity, Btu/(hr)(ft)(^oR)

L — critical length from tube entrance to burnout point, ft

N_B — boiling number (fluid property parameter), $\frac{\sqrt{g}\,\mu_v^2\,\sqrt{\rho_l - \rho_v}}{\rho_v(g_c\sigma_L)^{1.5}}$, dimensionless

P — static pressure, lb/sq in. abs

P_{cr} — thermodynamic critical pressure for fluid; 3206, 493, and 188 lb/sq in. abs for water, nitrogen, and hydrogen, respectively

Pr — Prandtl number, $\mu c_p/k$, dimensionless

Q — total heat input from tube entrance to burnout point, Btu/hr

q	heat flux per unit surface area, $Q/\pi DL$, Btu/(hr)(sq ft)
Re	Reynolds number, GD/μ, dimensionless
W	weight-flow rate of fluid, $G \frac{\pi D^2}{4}$, lb_m/hr
X_C	critical vaporization parameter, $\frac{Q/W}{\Delta h}$, dimensionless
μ	fluid viscosity, lb_m/hr, ft
ρ	fluid density, lb_m/cu ft
σ_l	fluid surface tension, lb_f/ft

Subscripts:

C	critical value of heat flux (burnout condition)
f	force
l	liquid
m	mass
s	saturation property values at conditions associated with burnout location
v	vapor

APPENDIX B

SIGNIFICANCE OF COMPONENT TERMS IN FLUID PROPERTY PARAMETERS

The significance of individual as well as combined fluid property terms in equation (9) may be of interest to researchers who wish to evaluate the desirability of eliminating certain parameters as being of secondary importance in a specific range of operating conditions. In order to aid in this evaluation as well as show the general import of the fluid property terms, the component parts of equation (9) are shown in figure 6 as a function of the ratio of the saturation pressure at burnout condition to the thermodynamic critical pressure for the particular fluid P_s/P_{cr}. This pressure ratio was selected as a criterion to put all the fluids on a reasonable abscissa and as having been previously used in pool boiling studies for comparative purposes. However, it is also necessary to consider the effects of the fluid property parameters on the basis of absolute pressure level in order to obtain a better understanding of their significance.

The thermodynamic and transport data used in the computation of results were compiled from several sources, some published (refs. 11 to 15) and some unpublished. Since there are insufficient saturation property data for all the fluids used herein, particularly the cryogenic fluids, the author extrapolated the available data for his own use.

In terms of pressure ratio, the variation of the component parts of equation (9) exhibits the same general trends for the three fluids (water, nitrogen, and hydrogen) shown in figure 6. The curves, of course, are separated according to the properties peculiar to each fluid. The separation between the extremes of the curves may amount to as much as two orders of magnitude (see surface tension for water and hydrogen, fig. 6(d)) or as little as 50 percent (see N_B term for nitrogen and hydrogen, fig. 6(e)). From figures 6(d) and (e) it appears that the effect of pressure level for a specific fluid is correlated primarily by the N_B parameter wherein surface tension is the governing term at pressure ratios greater than about 0.2, while the density and viscosity terms predominate at pressure ratios less than about 0.2. The fluid property parameters in equation (9), other than N_B (figs. 6(a) to (c)), influence the correlation of the critical vaporization parameter increasingly more with increasing pressure ratio, especially at pressure ratios greater than about 0.6; however, their effect, compared with N_B, is of greater significance when different fluids are considered than when pressure ratio variations for the same fluid are considered.

The importance of considering fluid properties in terms of absolute pressure level is illustrated by considering figure 7 in which a summation of all the fluid property parameters in equation (9) is plotted as a function of pressure ratio. It is apparent that both the property differences between fluids, indicated by the spread between the curves, and the pressure ratio, indicated by the shape of the curves, strongly influence the magnitude of the fluid property parameters expressed in equation (9). However, at a given pressure level (e.g., 14.7 lb/sq in. abs), the fluid property parameters for hydrogen and water are substantially the same, while nitrogen has a value about one-fourth that of the other two fluids. Such a comparison, on the basis of an absolute pressure level, would change drastically as the absolute pressure level approaches 188 pounds per square inch absolute, the critical pressure for hydrogen for which condition the P_s/P_{cr} values for water and nitrogen would still be less than 0.4 (fig. 7).

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TABLE I. - DATA SELECTION AND RANGE OF VARIABLES USED FOR CORRELATION PROCEDURES

Reference	Nominal fluid pressure at burnout location, lb/sq in. abs	Data points with net vapor generation		Tube diameter, in.	Critical tube length-to-diameter ratio	Nominal liquid subcooling at inlet, °F	Mass velocity, $lb_m/(sq\ ft)(hr)$	Heat flux, Btu/(sq ft)(hr)
		Total number in reference	Number considered valid for correlation					
				Water				
2, Table III	14.7	487	487	0.051 to 0.188	25 to 250	~136	0.02 to 25.2×10^6	0.061 to 13.2×10^6
5	500	20	20	0.1805	52	39 to 361	0.03 to 0.075	0.104 to 0.38
5	1000	18	17	↓	↓	52 to 446	0.021 to 0.073	0.092 to 0.35
5	1500	12	11	↓	↓	66 to 495	0.021 to 0.033	0.082 to 0.16
5	2000	17	16	↓	↓	63 to 540	0.028 to 0.063	0.072 to 0.27
9	2000	[a]4	4	0.143	21	0 to 32	1.18 to 5.23	1.23 to 1.91
9	2000	[b]3	2	0.226	109	62 and 262	0.97 and 3.54	0.78 and 1.15
8	2000	21	18	0.186	64.5	24 to 242	0.21 to 3.52	0.34 to 1.02
10	550	21	21	0.1805	50	10 to 225	0.94 to 2.13	1.82 to 2.86
10	1000	25	25	0.1805	50	5 to 316	0.86 to 1.91	1.29 to 2.08
10	1500	13	10	0.1805	50	67 to 277	0.86 to 1.88	1.14 to 1.67
6	1000	15	2	0.187	67	131	1.23 and 2.36	1.57 and 1.97
6	2000	33	17	0.187	67	5 to 289	0.41 to 5.51	0.69 to 1.52
7	600	75	38	0.306	76	0 to 267	0.43 to 1.76	0.70 to 1.99
7	1000	41	27	↓	↓	0 to 361	0.41 to 1.64	0.72 to 1.74
7	2000	103	88	↓	↓	3 to 332	0.17 to 2.25	0.21 to 0.83
7	600 to 2000	[c]250	0	0.180	64.5	0 to 140	0.75 to 6.34	0.53 to 2.16
				Nitrogen				
3	50	11	10	0.555	29	3	0.016 to 0.056	0.009 to 0.024
				Hydrogen				
3	50	44	44	0.555	4.5 to 28	0 to 6	0.0028 to 0.164	0.0059 to 0.021

[a]In addition, two data points at 500, one at 1200, and three at 3000 lb/sq in. abs were discarded.
[b]In addition, nine data points at 500 to 1300 lb/sq in. abs were discarded.
[c]All data fall below 70 percent of maximum critical heat flux values reported by other investigators; all data discarded.

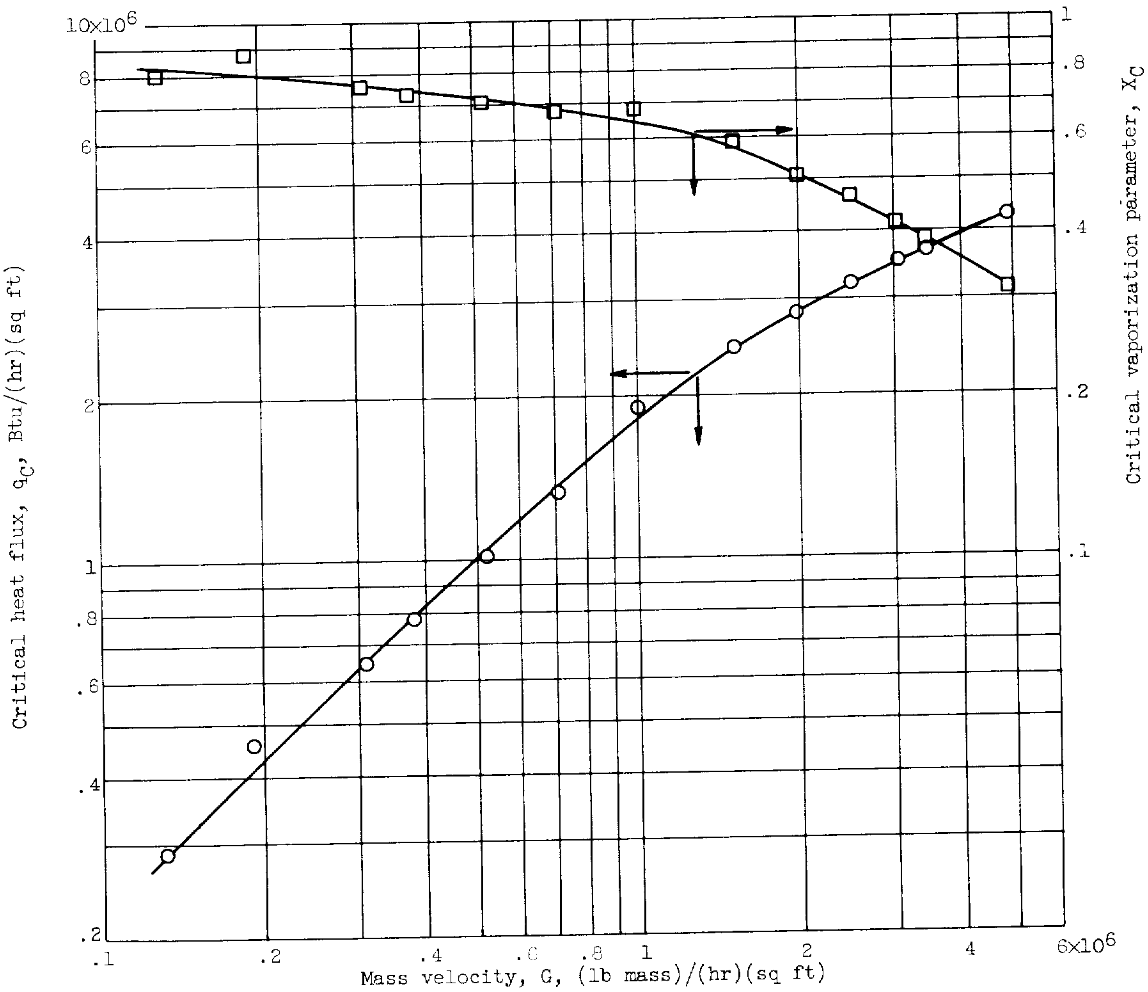
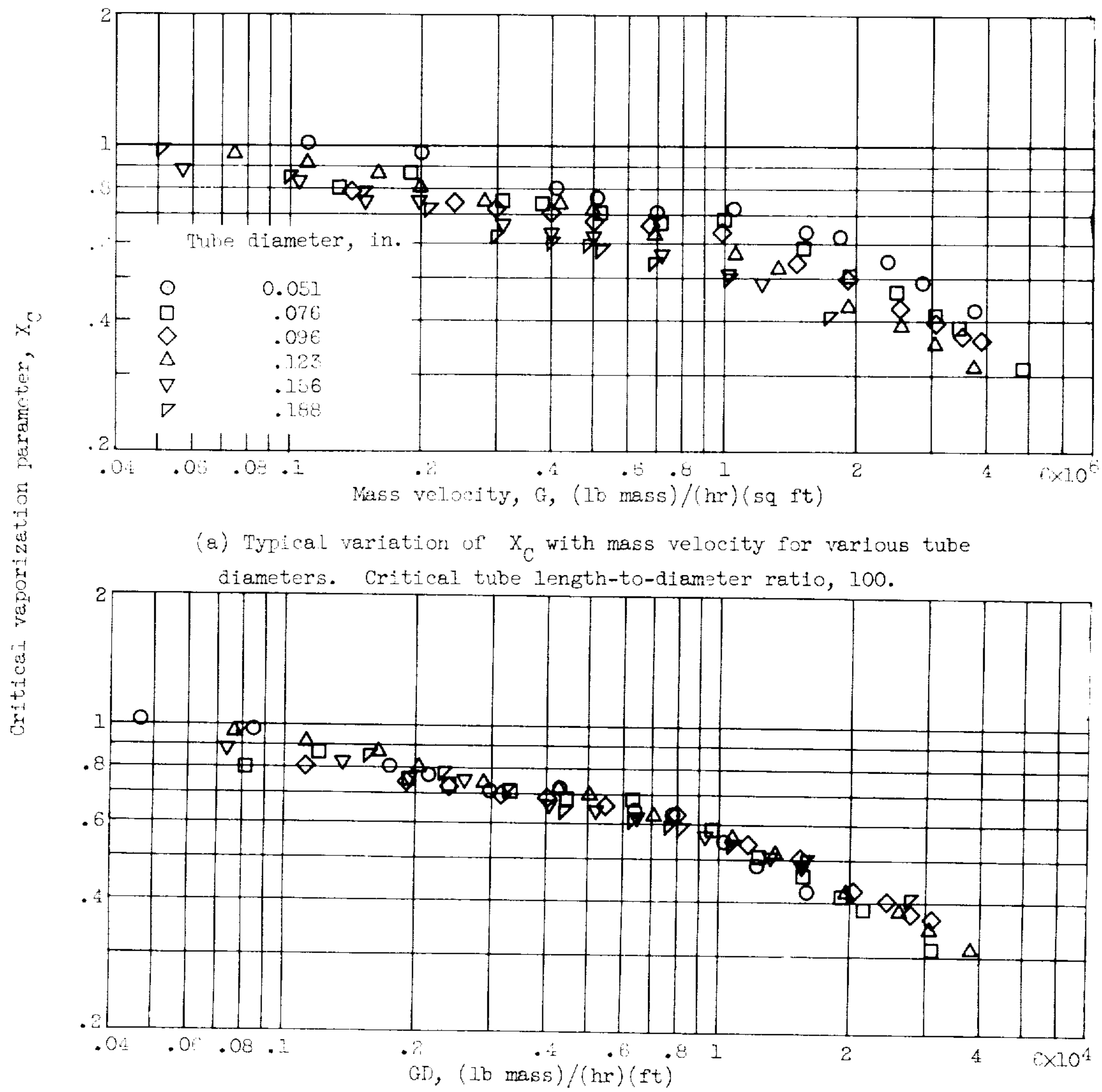


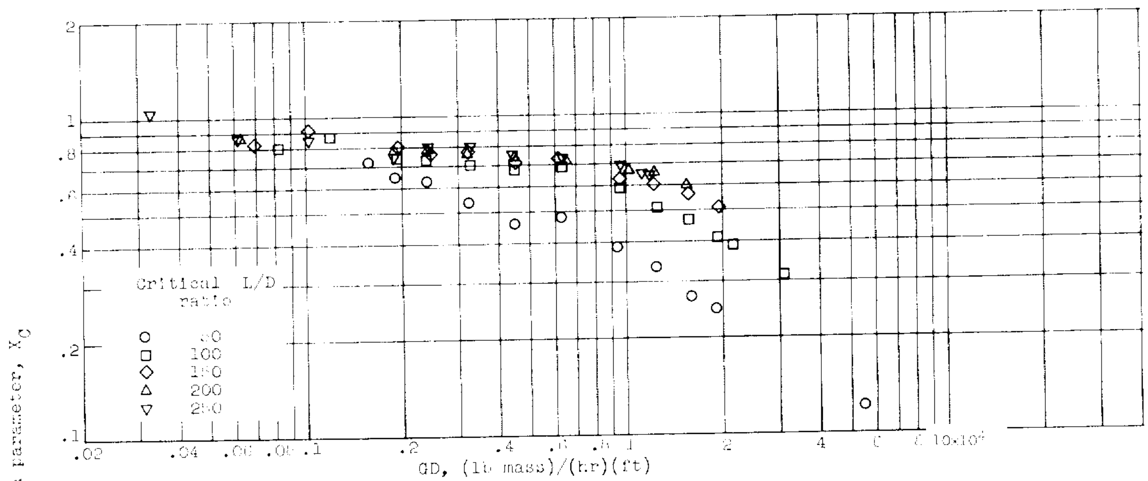
Figure 1. - Typical variation of critical heat flux and critical vaporization parameter with mass velocity (data from ref. 2). Fluid, water; pressure at burnout point, 14.7 pounds per square inch absolute; inlet temperature of liquid, 76° F; tube diameter, 0.076 inch; critical L/D ratio, 100.



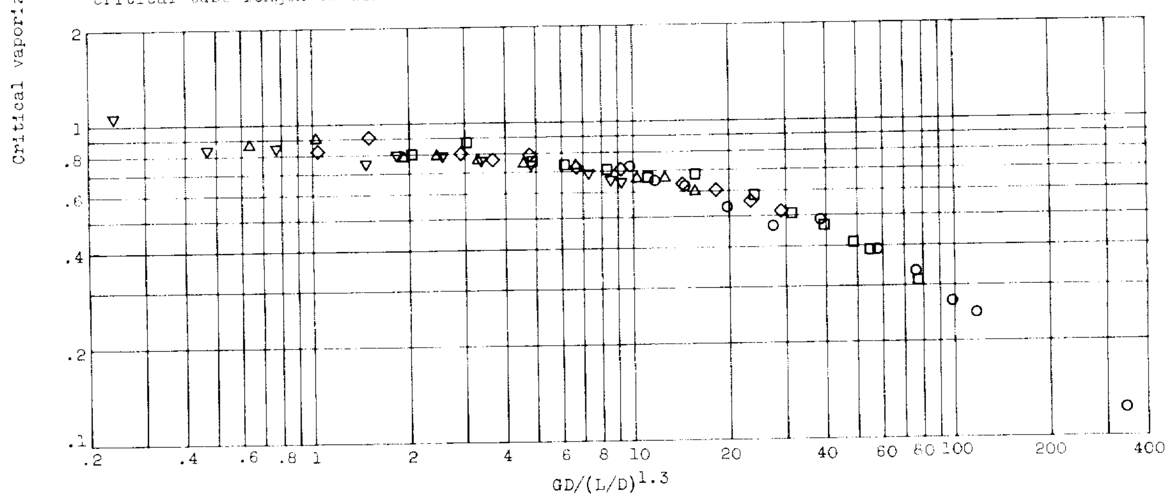
(a) Typical variation of X_c with mass velocity for various tube diameters. Critical tube length-to-diameter ratio, 100.

(b) Correlation of tube diameter effect. Critical tube length-to-diameter ratio, 100.

Figure 2. - Typical correlation of critical vaporization parameter X_c with mass velocity, critical tube length-to-diameter ratio, and tube diameter (data from ref. 2). Fluid, water; pressure at burnout location, 14.7 pounds per square inch absolute.

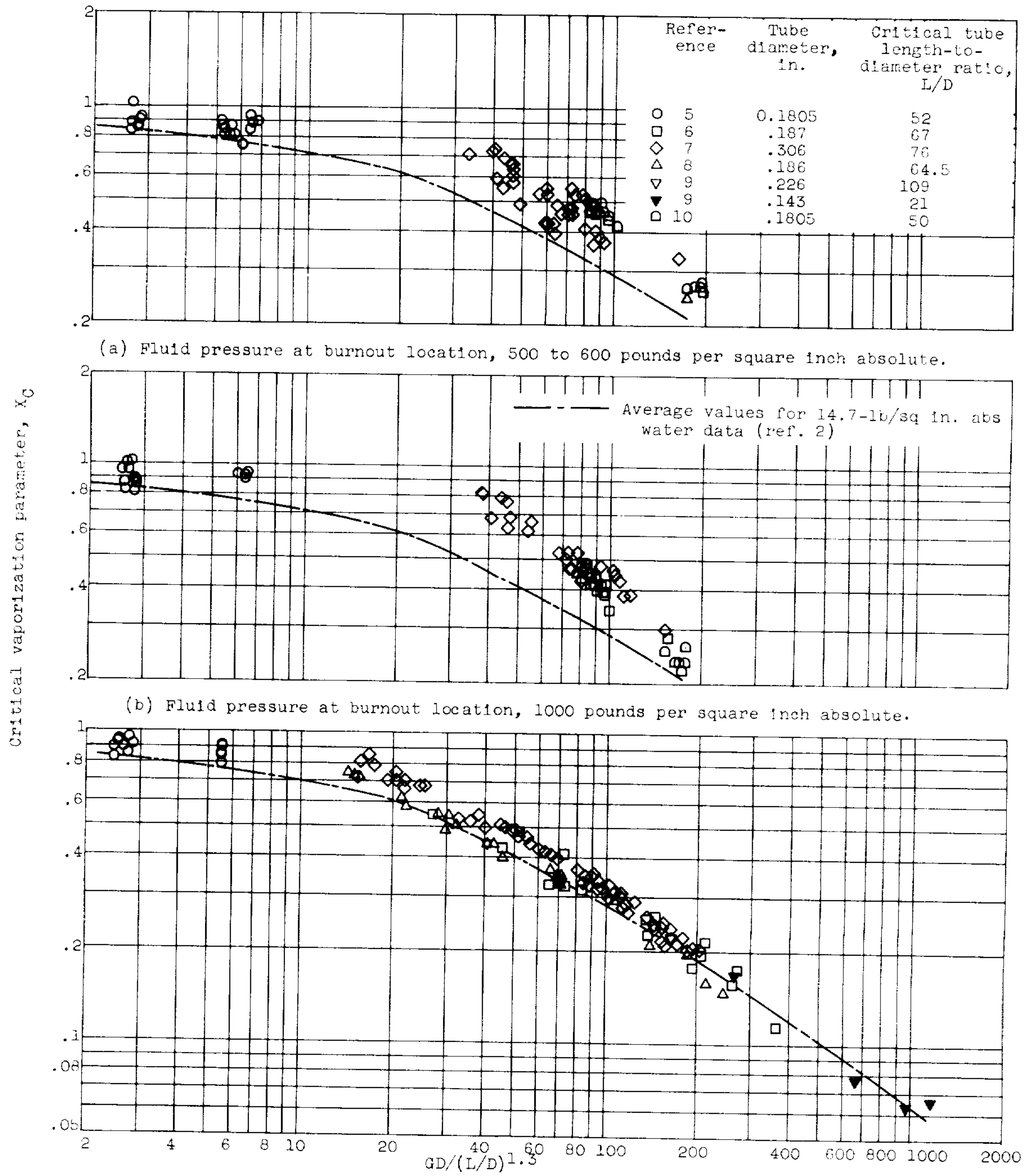


(c) Typical variation of X_c with product of mass velocity and tube diameter for various critical tube length-to-diameter ratios. Tube diameter, 0.076 inch.



(d) Correlation of critical tube length-to-diameter effect.

Figure 2. - Concluded. Typical correlation of critical vaporization parameter X_c with mass velocity, critical tube length-to-diameter ratio, and tube diameter (data from ref. 2). Fluid, water; pressure at burnout location, 14.7 pounds per square inch absolute.



(a) Fluid pressure at burnout location, 500 to 600 pounds per square inch absolute.

(b) Fluid pressure at burnout location, 1000 pounds per square inch absolute.

(c) Fluid pressure at burnout location, 2000 pounds per square inch absolute.

Figure 3. - Variation of critical vaporization parameter X_c with $GD/(L/D)^{1.3}$ for several fluid pressure levels at burnout location. Fluid, water.

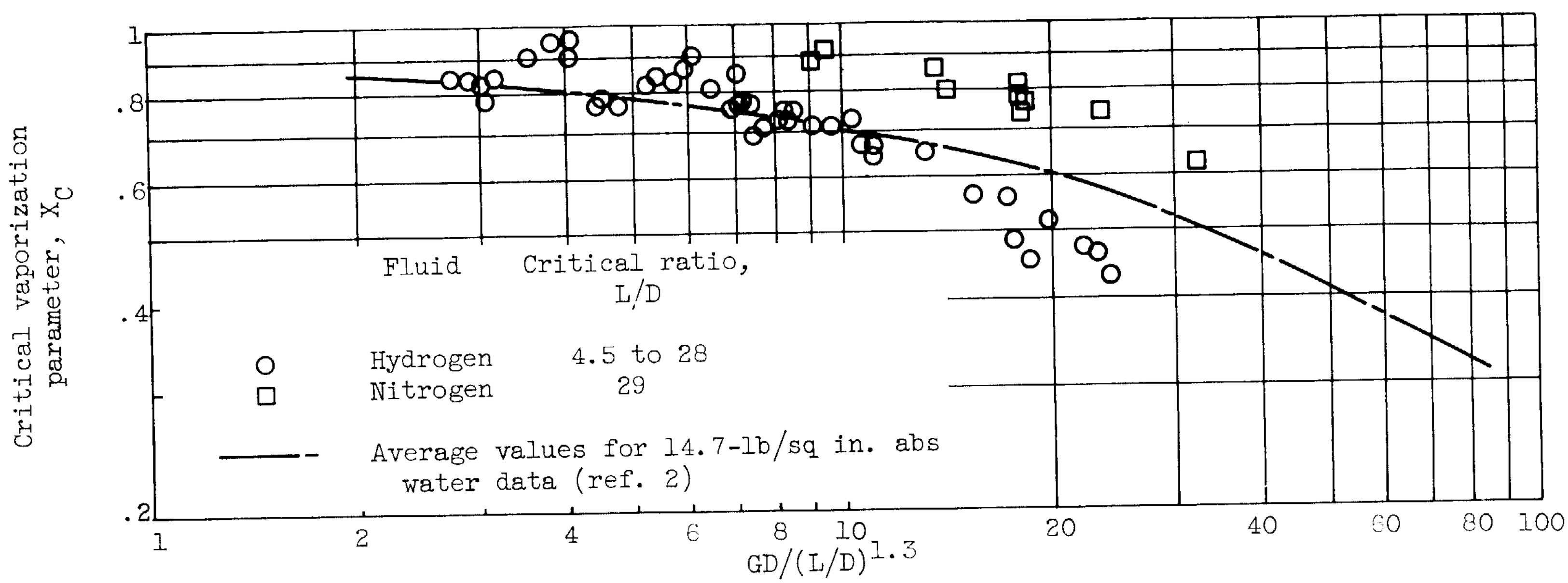
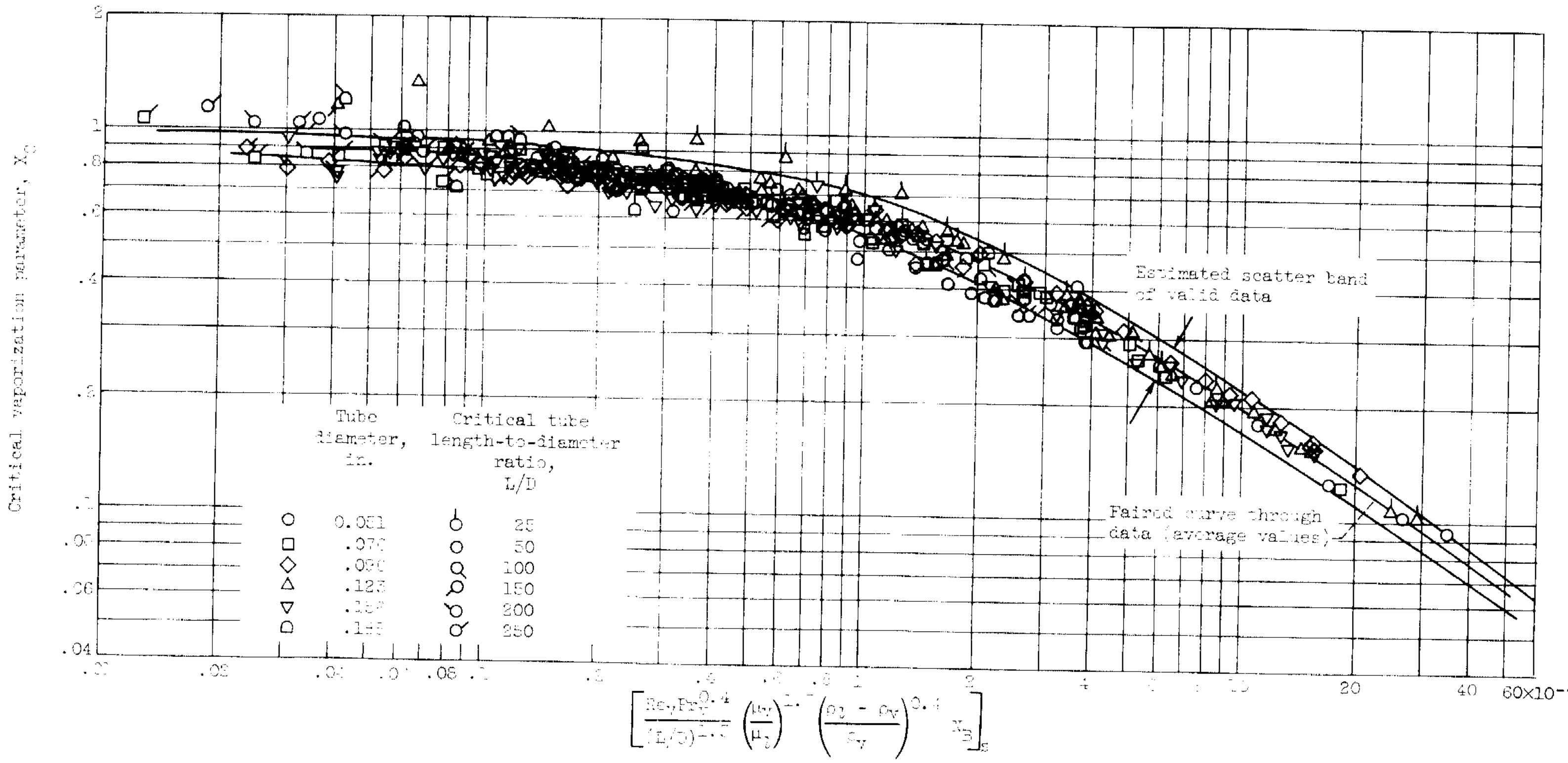
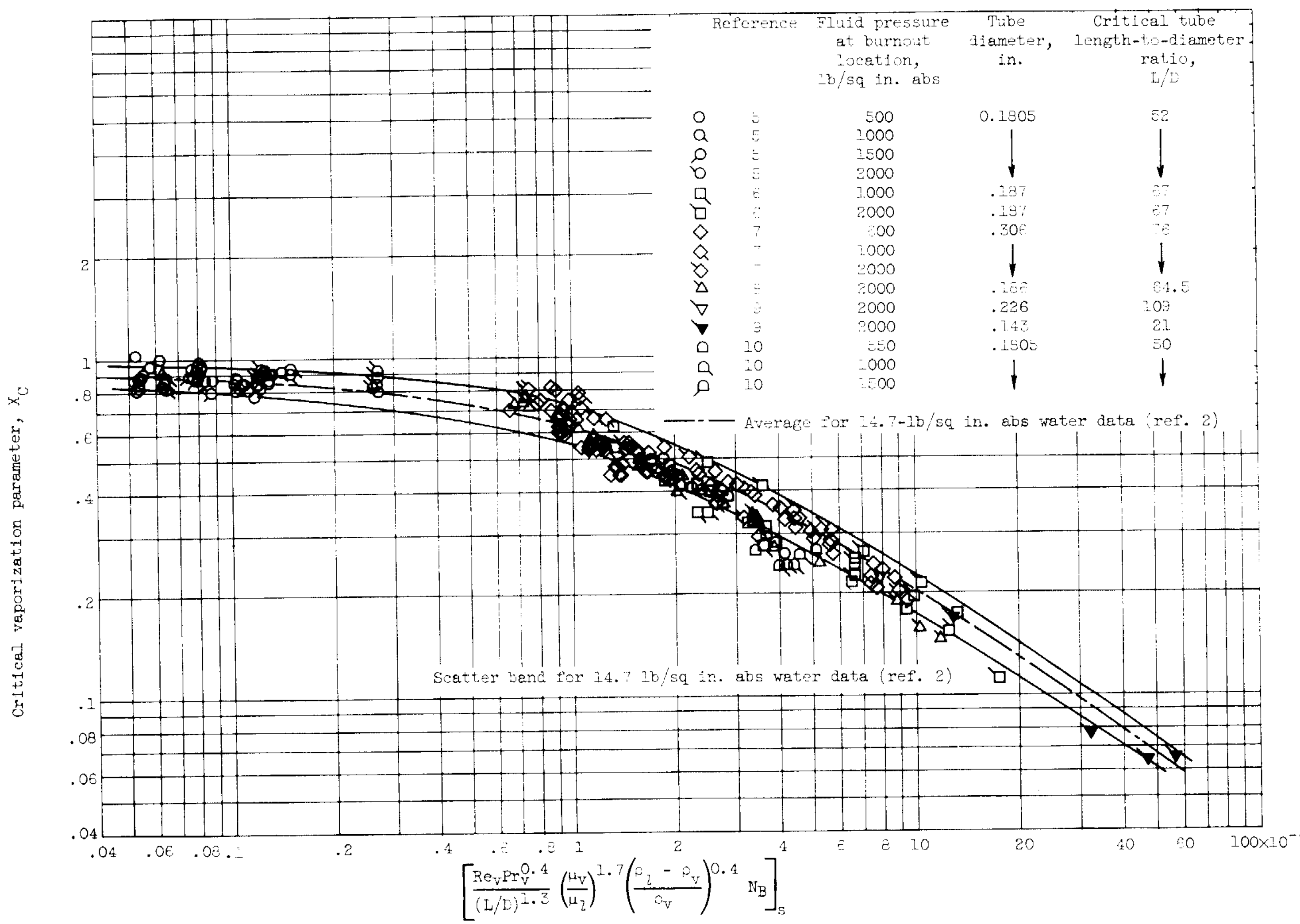


Figure 4. - Correlation of critical vaporization parameter X_C with $GD/(L/D)^{1.3}$ for hydrogen and nitrogen (data from ref. 3). Tube diameter, 0.555 inch; fluid pressure at burnout location, ~50 pounds per square inch absolute.



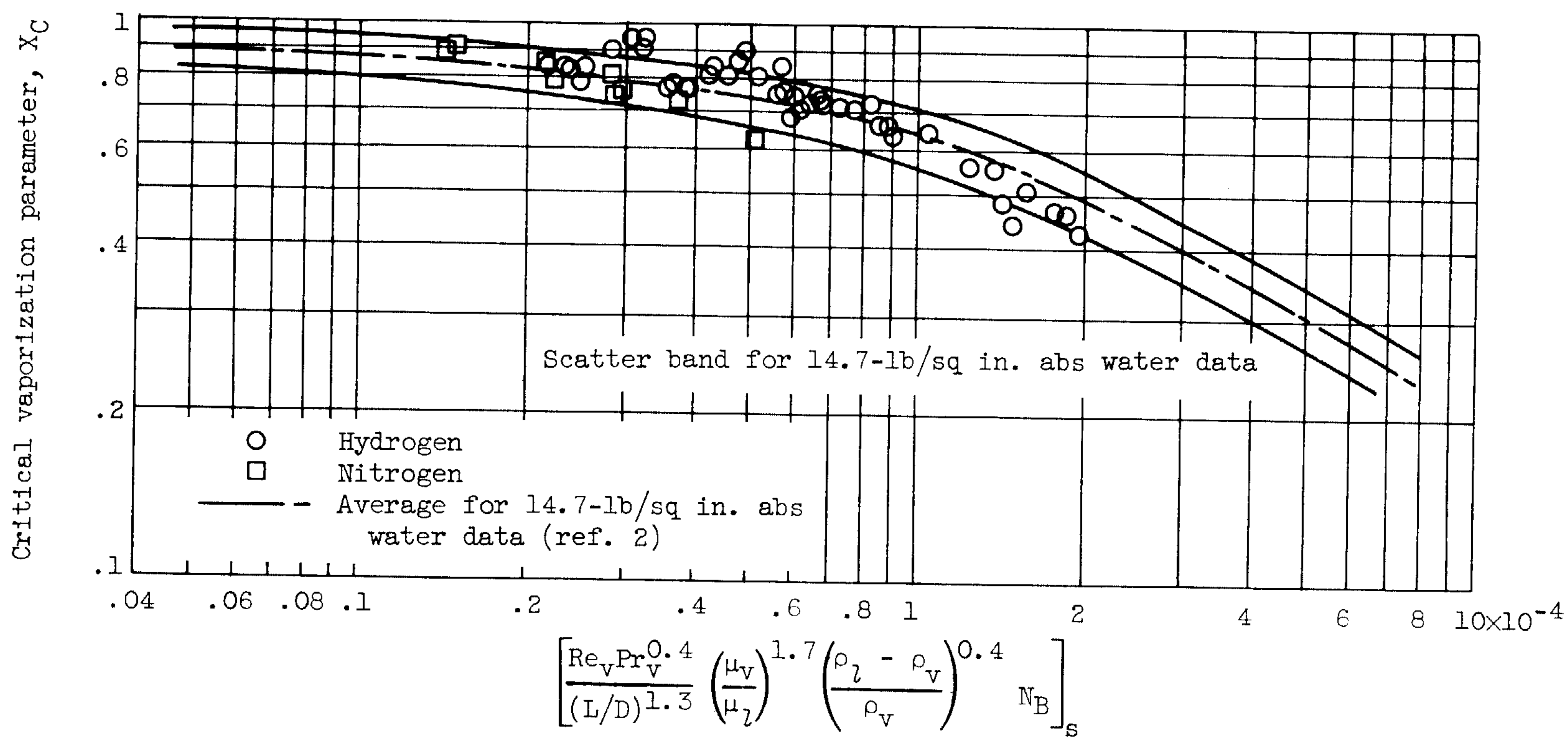
(a) Fluid, water; fluid pressure at burnout location, 1.4[illegible] pounds per square inch absolute; data from reference 2.

Figure [illegible]. - Correlation of critical vaporization parameter X_C for net vapor generation in terms of tube geometry, flow rate, and fluid properties.



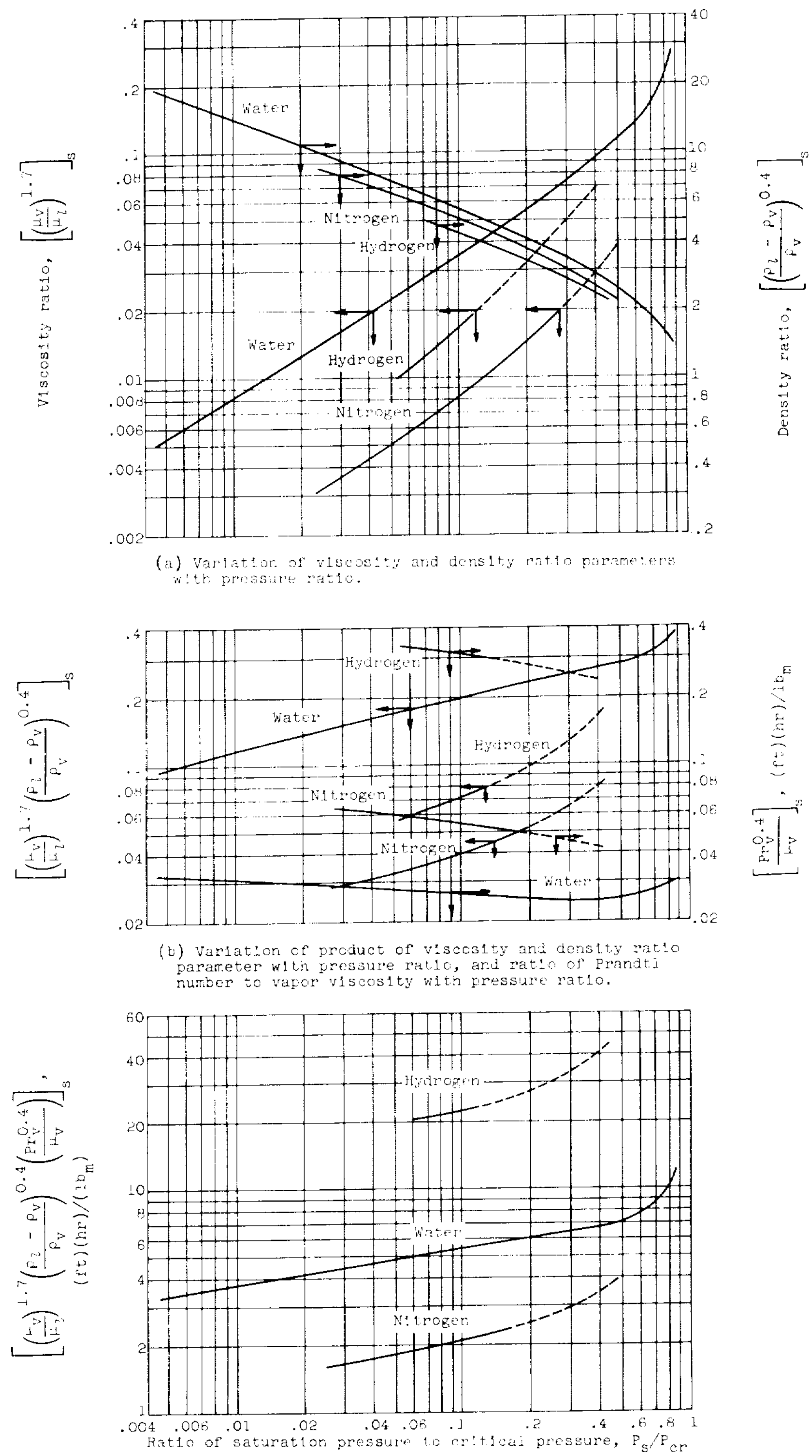
(b) Fluid, water; fluid pressure at burnout location, 500 to 2000 pounds per square inch absolute.

Figure 5. - Continued. Correlation of critical vaporization parameter X_C for net vapor generation in terms of tube geometry, flow rate, and fluid properties.



(c) Fluids, hydrogen and nitrogen; fluid pressure at burnout location, ~50 pounds per square inch absolute; data from reference 3.

Figure 5. - Concluded. Correlation of critical vaporization parameter X_C for net vapor generation in terms of tube geometry, flow rate, and fluid properties.

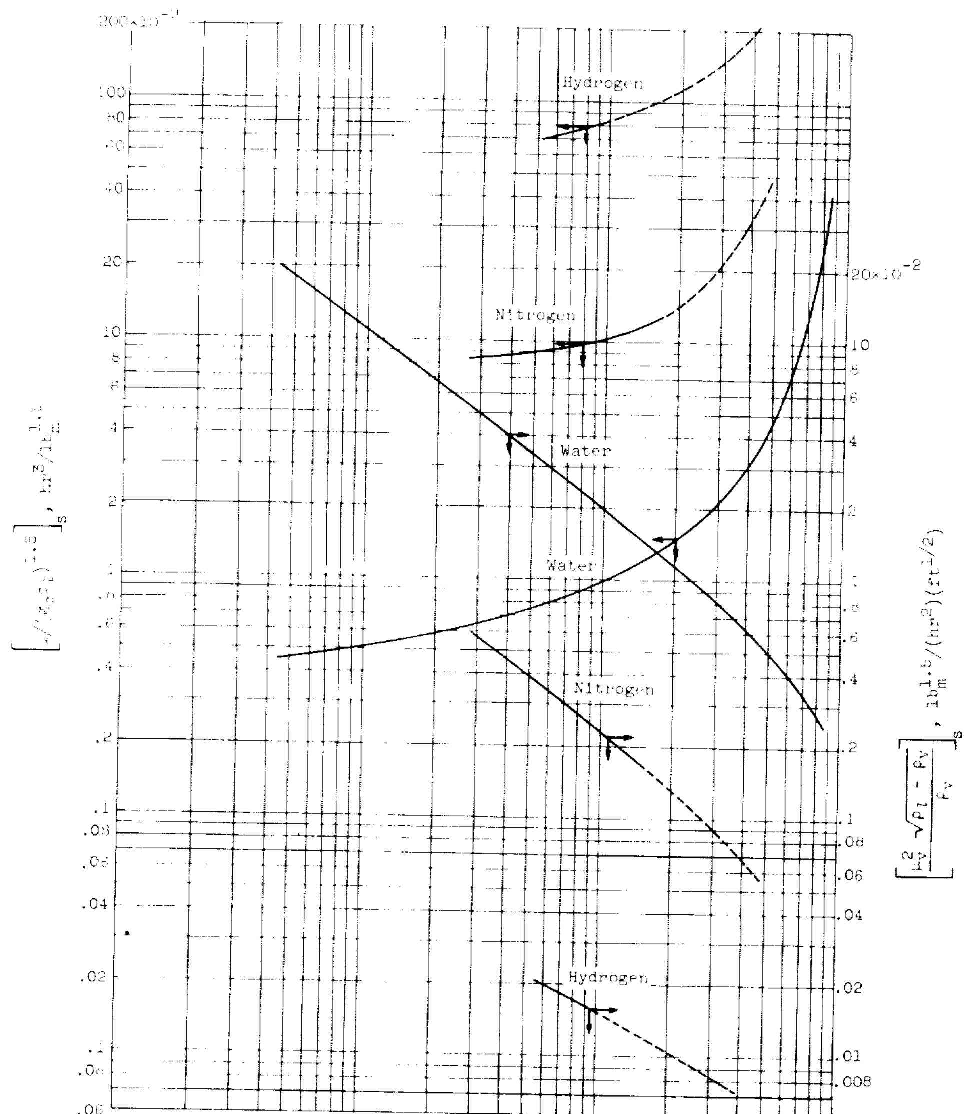


(a) Variation of viscosity and density ratio parameters with pressure ratio.

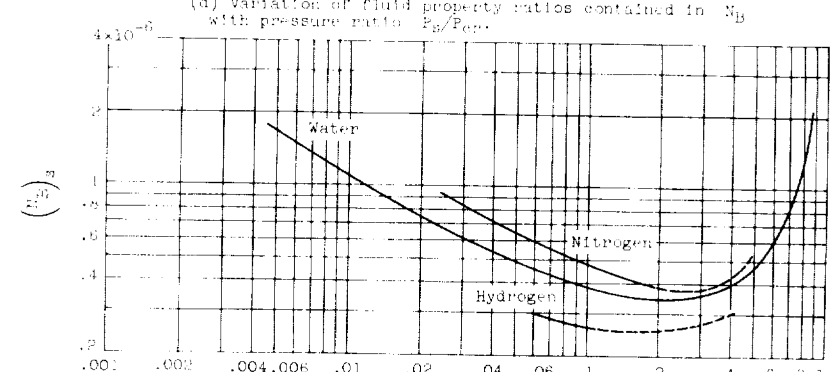
(b) Variation of product of viscosity and density ratio parameter with pressure ratio, and ratio of Prandtl number to vapor viscosity with pressure ratio.

(c) Variation of product of viscosity and density ratios times ratio of Prandtl number to vapor viscosity with pressure ratio.

Figure 6. - Variation of fluid property ratios and parameters with pressure ratio P_s/P_{cr} at saturation.



(d) Variation of fluid property ratios contained in N_B with pressure ratio P_s/P_{cr}.



(e) Variation of N_B with pressure ratio, P_s/P_{cr}.

Figure 6. - Concluded. Variation of fluid property ratios and parameters with pressure ratio P_s/P_{cr}.

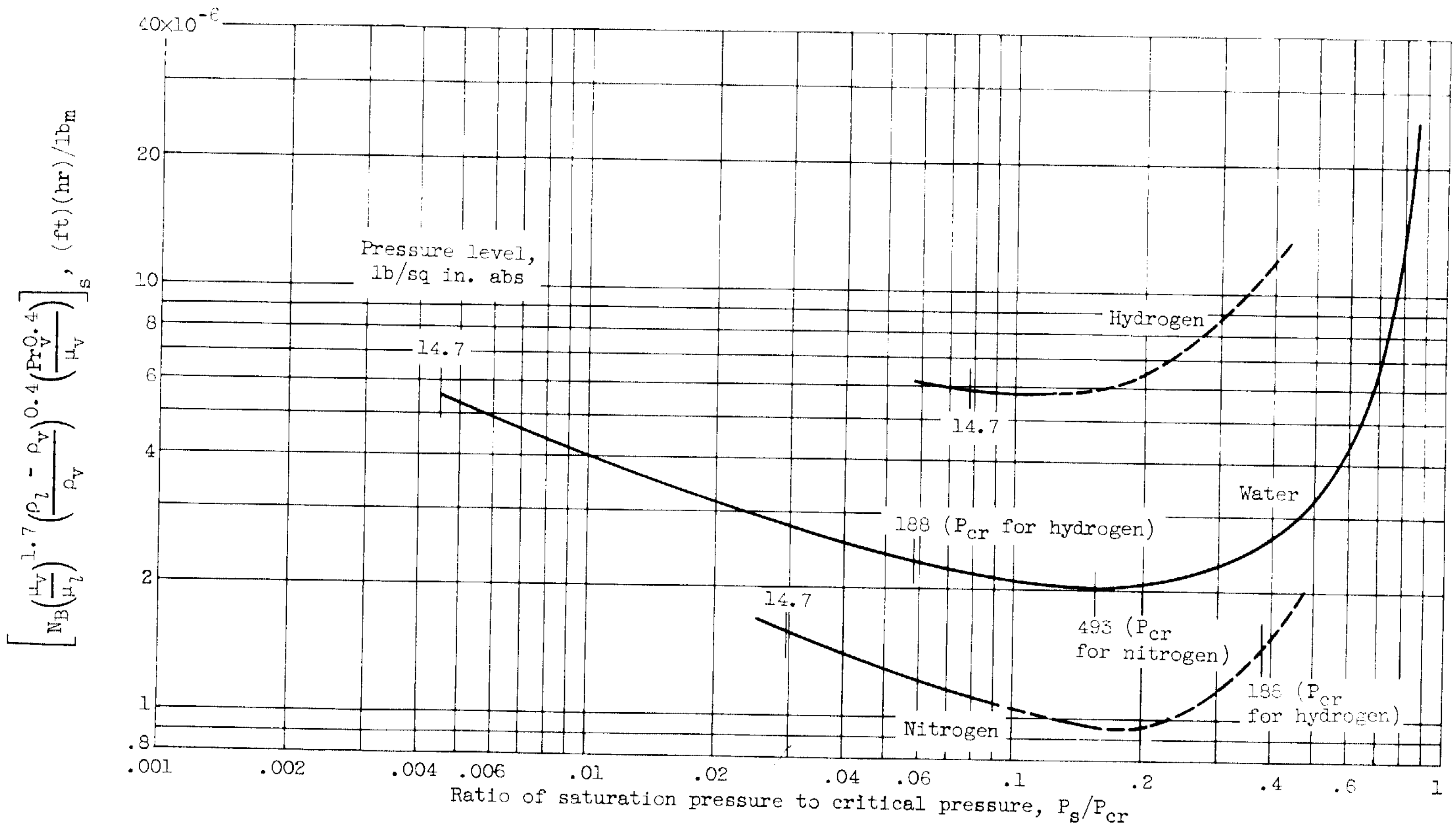


Figure 7. - Summation of all fluid property parameters as a function of pressure ratio.